Dust in Planetary Systems
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Electrostatic Barrier Against Dust Growth in Protoplanetary Disks

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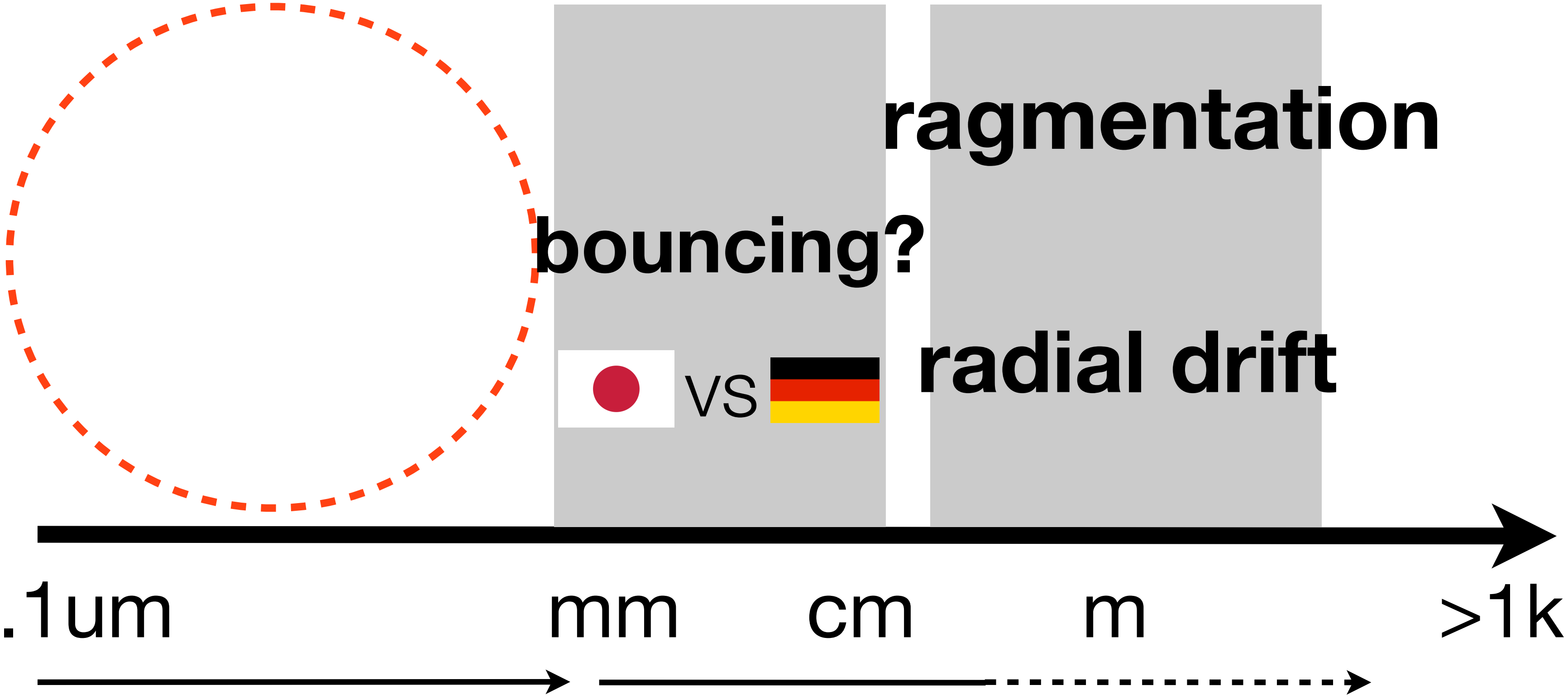
Ref: Okuzumi 2009, ApJ, 698, 1122
Okuzumi et al. 2009, ApJ, 707, 1247
Okuzumi et al., submitted, arXiv:1009.3199; 1009.3101

Barries Against Dust Growth in PP disks



ragmentation

bouncing?

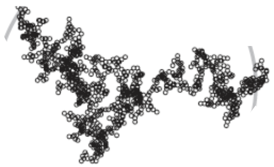
🇯🇵 vs 🇩🇪

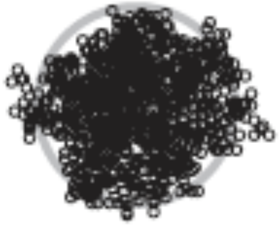
radial drift

0.1um mm cm m >1km

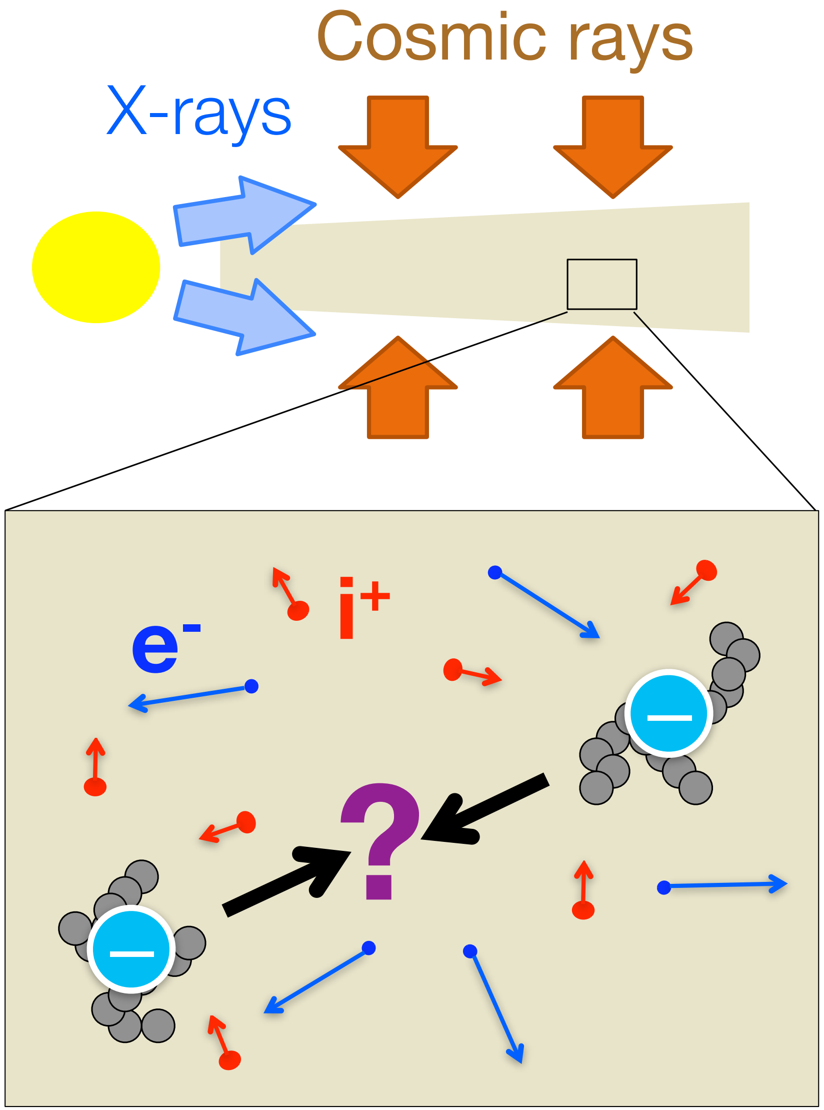
fractal growth

compaction





The “Charge Barrier” Against Dust Coagulation?



✴ PP-disks are **weakly ionized** by various high-energy sources:

- cosmic rays (e.g., Umebayashi & Nakano 80)
- stellar X-rays (e.g., Glassgold et al. 97)

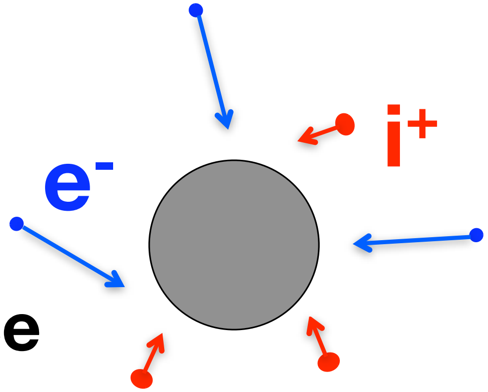
✴ Dust particles in an ionized gas: (on average) get **negative** charges!

(first discovered in astrophysics (Spitzer 41), now better known in plasma physics)

✴ “Assymmetric” (⟨Q⟩≠0) charging

➡ Coulomb barrier between colliding particles

Prelude: Grain Charging in a *Fully* Ionized Gas



- number density: $n_i \approx n_e \quad (\ll |Q| n_d)$
- thermal speed: $v_i \ll v_e \quad (\Leftarrow m_i \gg m_e)$

➡ **incident flux:** $n_i v_i \ll n_e v_e$

➡ **the grain charges up until the Coulomb force equilibrates these fluxes.**

Equilibrium Condition: $\boxed{-eV \sim k_\mathrm{B} T}$

***V* = *Q*/*a*: surface potential of the grain** (e.g.,Spitzer 1941)

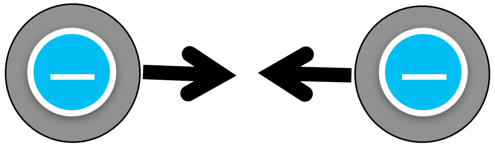
➡ $V \sim -\frac{k_\mathrm{B} T}{e} \sim -10\,\mathrm{mV}\left(\frac{T}{10^2\,\mathrm{K}}\right)$ ← independent of grain size *a*

➡ $Q = aV \sim -\text{a few}\; e\left(\frac{a}{0.1\,\mu\mathrm{m}}\right)\left(\frac{T}{10^2\,\mathrm{K}}\right)$ $\propto a$

Prelude: Collision of Charged Grains

Consider a collision between two charged grains

Hitting Condition: $\boxed{E_{\rm kin} > E_{\rm el}}$



- $E_{\rm kin} = \frac{1}{2} M_{\rm red} (\Delta v)^2$: kinetic energy
- $E_{\rm el} = \frac{Q_1 Q_2}{a_1 + a_2}$: electrostatic energy

Using Q = aV, $E_{\rm el} \sim aV^2 \sim \left(\frac{a}{0.1\ \mu{\rm m}}\right)\left(\frac{T}{10^2\ {\rm K}}\right) k_{\rm B} T \quad \propto a$

If the relative velocity is driven **only** by Brownian motion ($E_{\rm kin} \sim k_{\rm B} T$),

collision is severely inhibited at a >> 0.1um!!

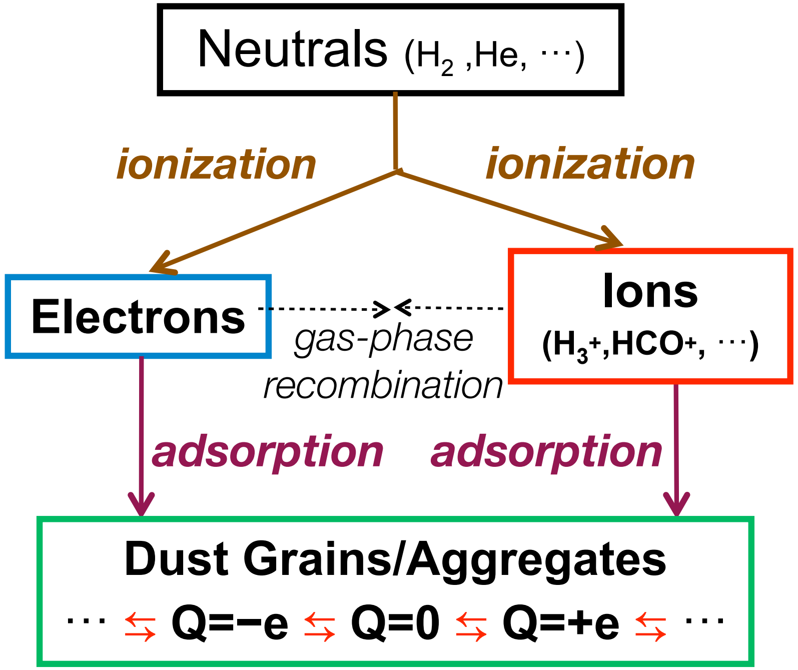
This Work

- Dust Charging in weakly ionized gases
- The role of the size distribution
- The effect of settling/turbulence

Dust Charging in Weakly Ionized Gases

✳ Dust charge distribution $n_d(Z)$
✳ Ion & electron number density n_i, n_e

are mutually dependent!
→ Must be computed simultaneously!


Neutrals (H_2 ,He, ⋯)

ionization

ionization

Electrons

Ions
(H_3^+,HCO^+, ⋯)

gas-phase recombination

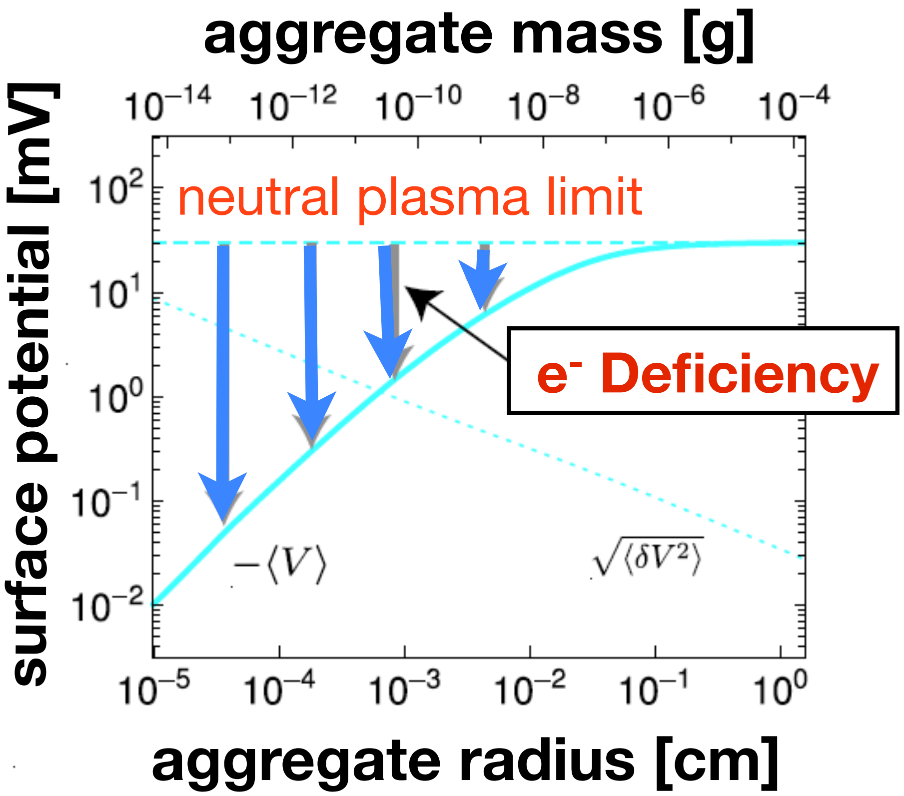
adsorption

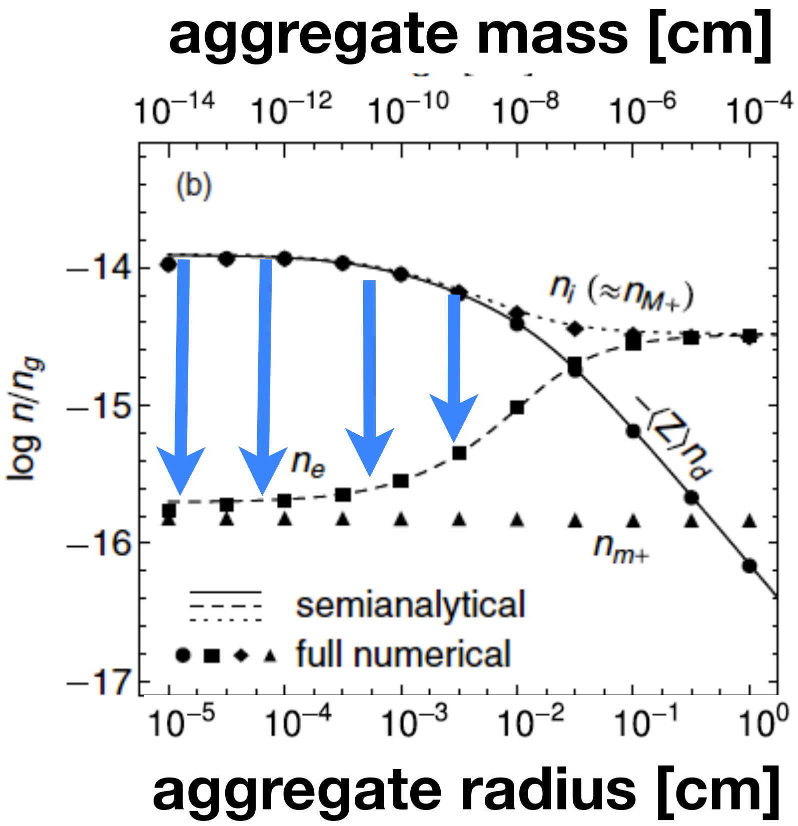
adsorption

Dust Grains/Aggregates
⋯ ⇆ Q=−e ⇆ Q=0 ⇆ Q=+e ⇆ ⋯

Electron Deficiency Effect (Okuzumi 2009)

MMSN + cosmic rays + X-rays, *r*=5AU, *z*=*H*
Fractal growth, D=2 (0.1um monomer)





Weak ionization prevents small aggregates from being strongly charged

Coagulation of Charged Dust: Simulations

- **Smoluchowski's method** to follow the evolution of size distribution
- **Collisional cross section *including Coulomb correction*:**

$$\boxed{\sigma_{\mathrm{eff}} = \pi(a_1 + a_2)^2 \left(1 - \frac{E_{\mathrm{el}}}{E_{\mathrm{kin}}}\right)} \quad E_{\mathrm{kin}} = \frac{1}{2}\frac{M_1 M_2}{M_1 + M_2}\Delta v^2 \quad E_{\mathrm{el}} = \frac{Q_1 Q_2}{a_1 + a_2} = \frac{a_1 a_2}{a_1 + a_2} V^2$$

✳ **Δv** : **Relative velocity =** Brownian motion **+ settling + turbulence**

✳ ***V*** : **Dust surface potential** ⬅ analytic solution by Okuzumi (2009)

- **"Hit-and-stick" (fractal) aggregation model** (Okuzumi et al. 2009)
  - no compaction nor fragmentation
  - determines the porosity of collision products using an empirical formula obtained from N-body calculations
- **Local (0-dim.) simulation** (advection is neglected)

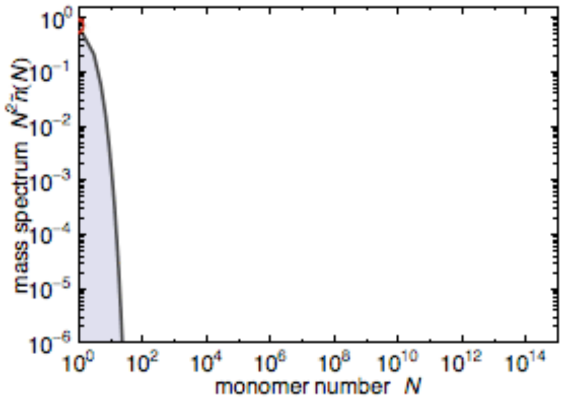
Key parameters: ionization rate ζ, "drift acceleration" *g*

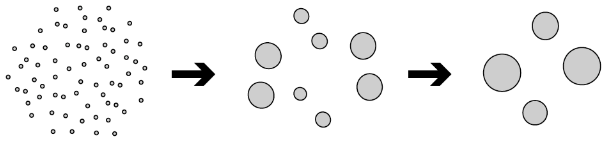
The Outcome of Dust Growth

Three types of outcomes depending on **ζ** & ***g*** :

(Okuzumi et al. submitted)

“Orderly” growth





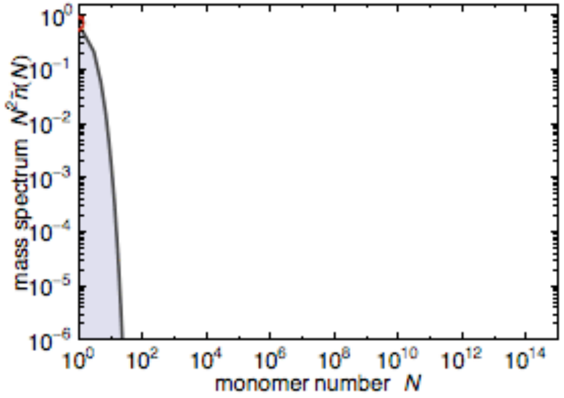
- **No-charging cases**
- **Relatively narrow size distribution**

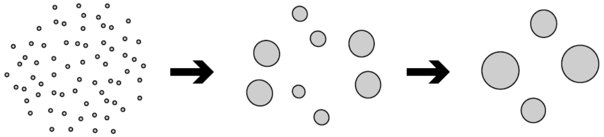
The Outcome of Dust Growth

Three types of outcomes depending on **ζ** & ***g*** :

(Okuzumi et al. 2010a, submitted)

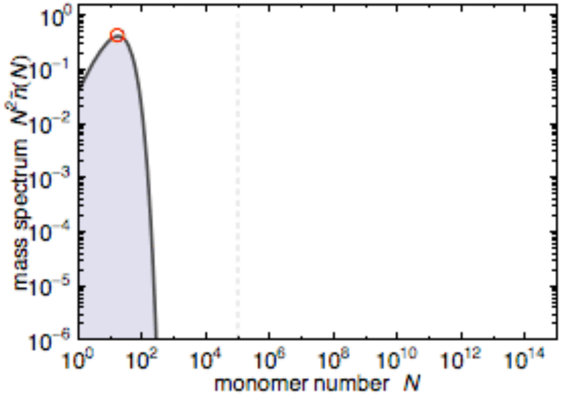
"Orderly" growth

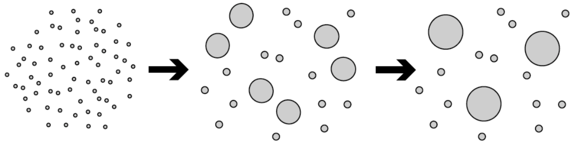




- **When *g* is high**
- **Charge does not affect the growth**

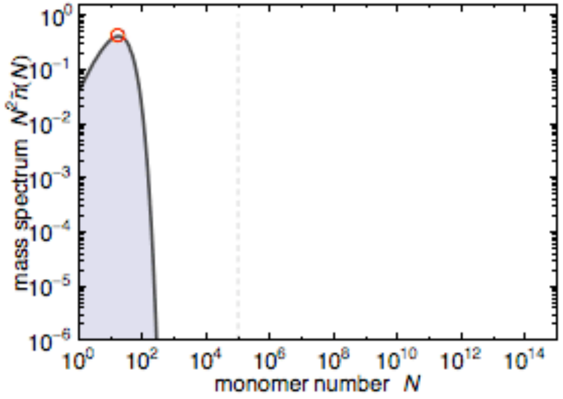
"Bimodal" growth

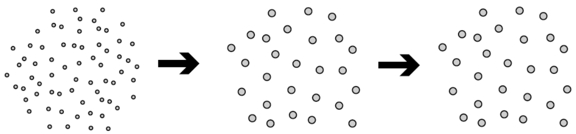




- **Low *g* but low ζ**
- ***Electron deficiency effect!***

"Freezeout"



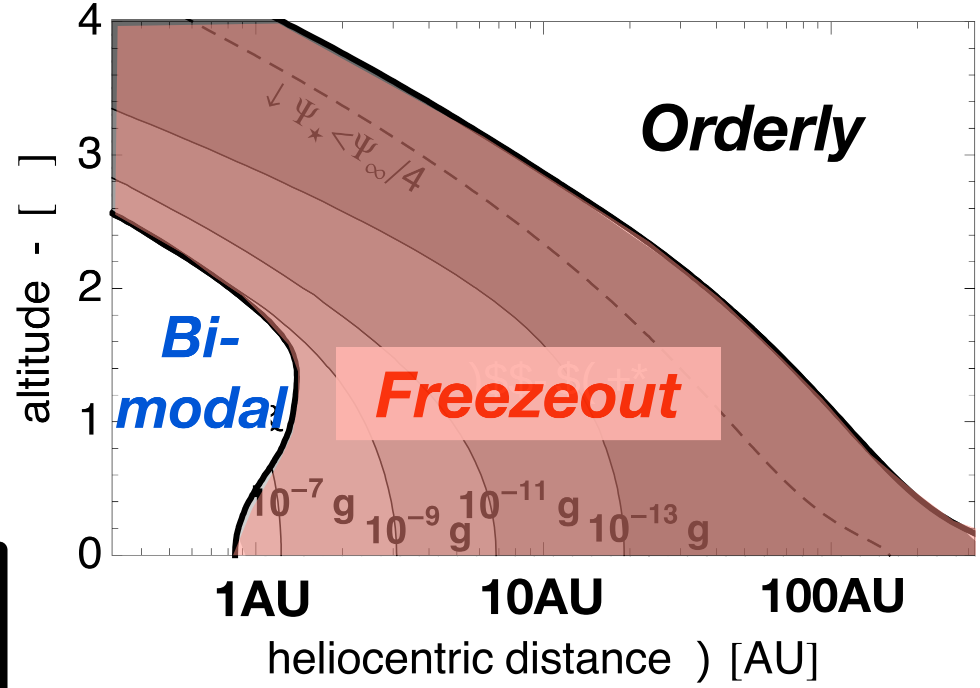


- **Low *g* & High ζ**
- **Growth stops in the Brownian motion regime**

Application to Protoplanetary Dust Growth

- ✓ MMSN model (Hayashi 81), isothermal
- ✓ Cosmic rays, stellar X-rays, ^{26}Al
- ✓ Monomer size: 0.1um
- ✓ Includes turbulence-driven collision velocity (but *ignores* turbulent diffusion)

(Okuzumi et al. 2010b, submitted)



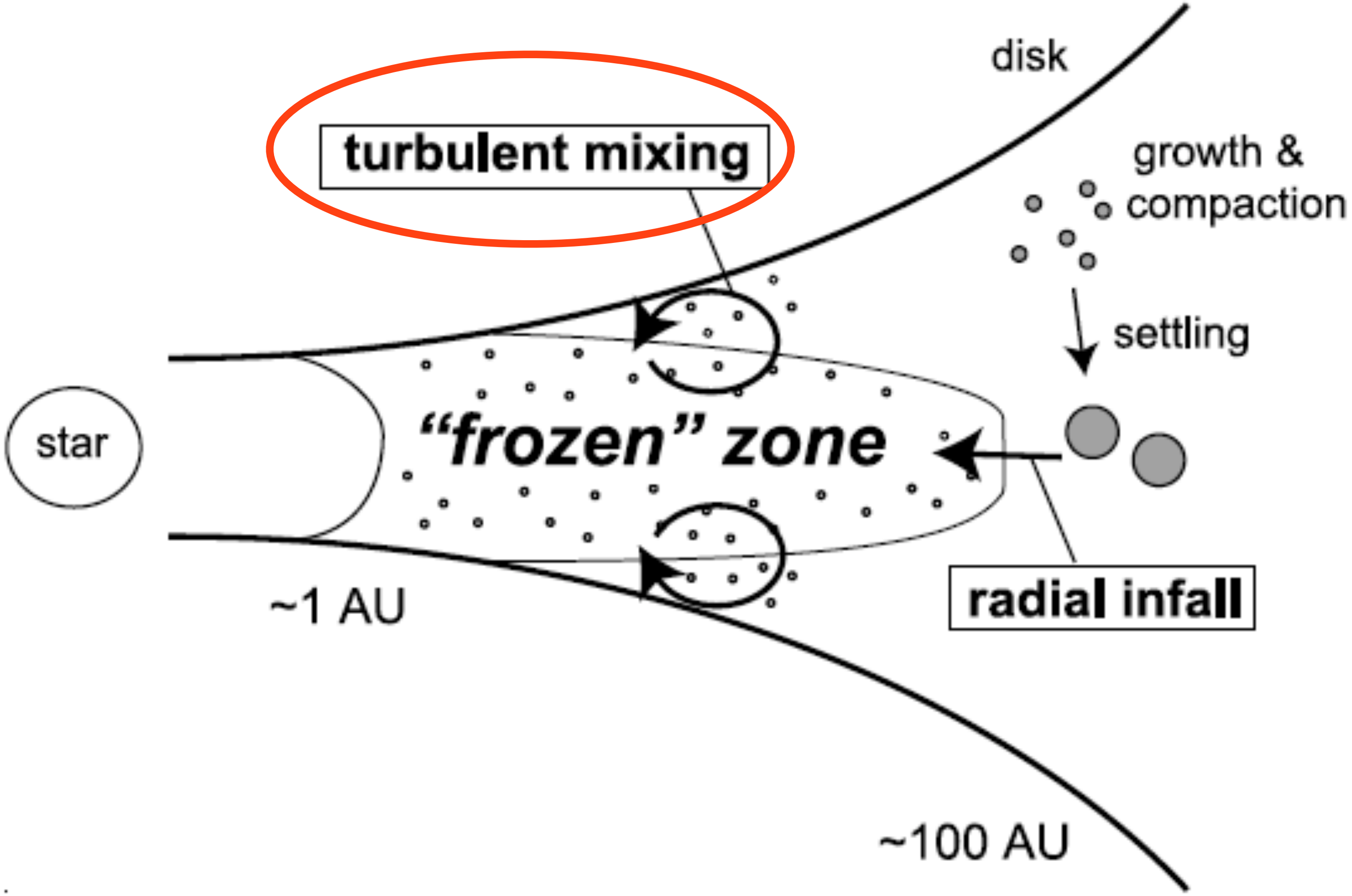
- **At depth≲0.1g/cm^2 , orderly growth**
  - ⬅ High collision velocity ⬅ **Low gas density**
- **At depth≳10^3 g/cm^2, bimodal growth**
  - ⬅ Electron deficiency ⬅ **Weak ionization**
- **At intermediate depths, freezeout!**

The maximum size of the “frozen” aggregates in the disk

10^{-7} g (0.1mm, 10^{-3} g/cc) !!

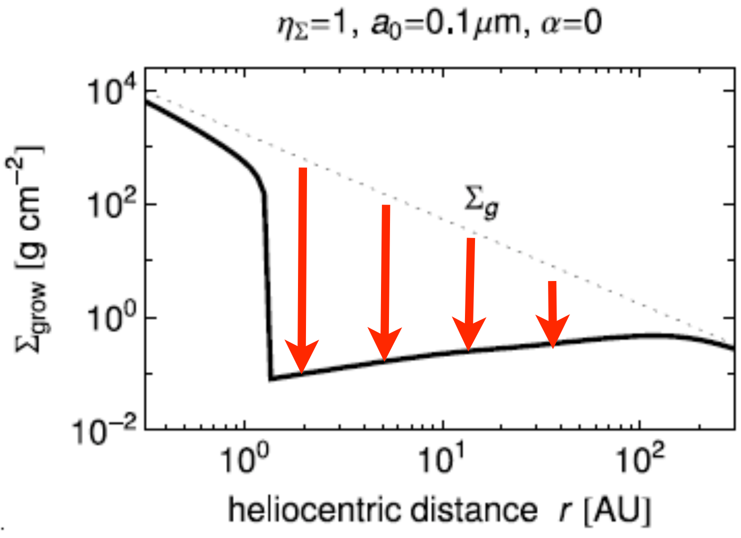
(<< M_{comp}~ 10^{-4} g)

Dust Transport Across Frozen-zone Boundaries



(Okuzumi et al. 2010b, submitted)

Dust Growth Timescales



Mean Collision Time at distance *r*

$$\tau_{\rm grow} \equiv \left(\frac{d\ln M}{dt}\right)^{-1}$$

W/o charging, $\tau_{\rm grow} \sim \frac{\Sigma_g}{\Sigma_d} T_{\rm K}$

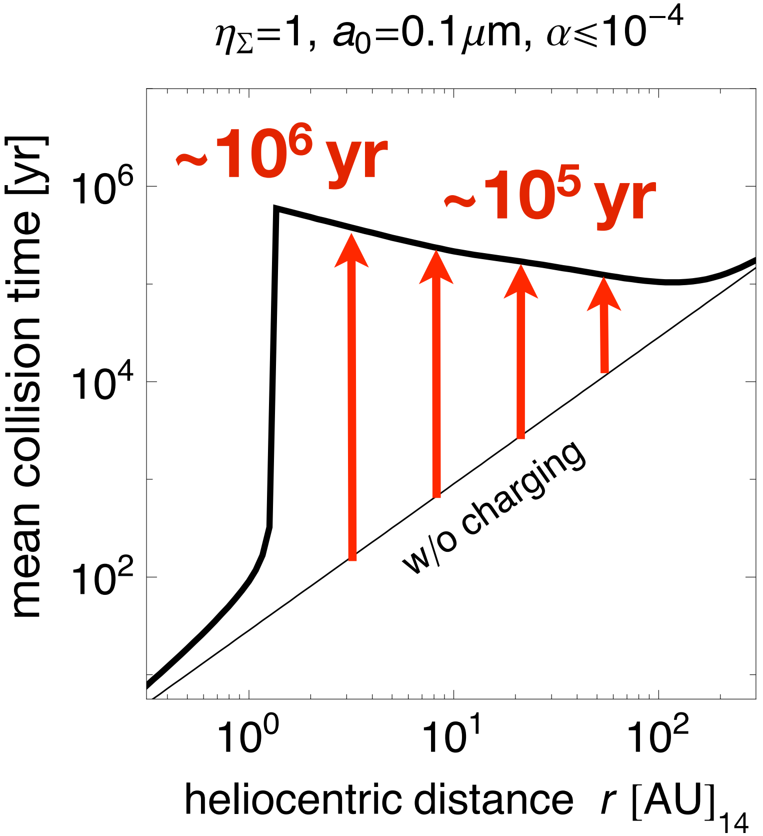
$\sim 10^2$ yr @1AU

$\sim 10^5$ yr @100AU

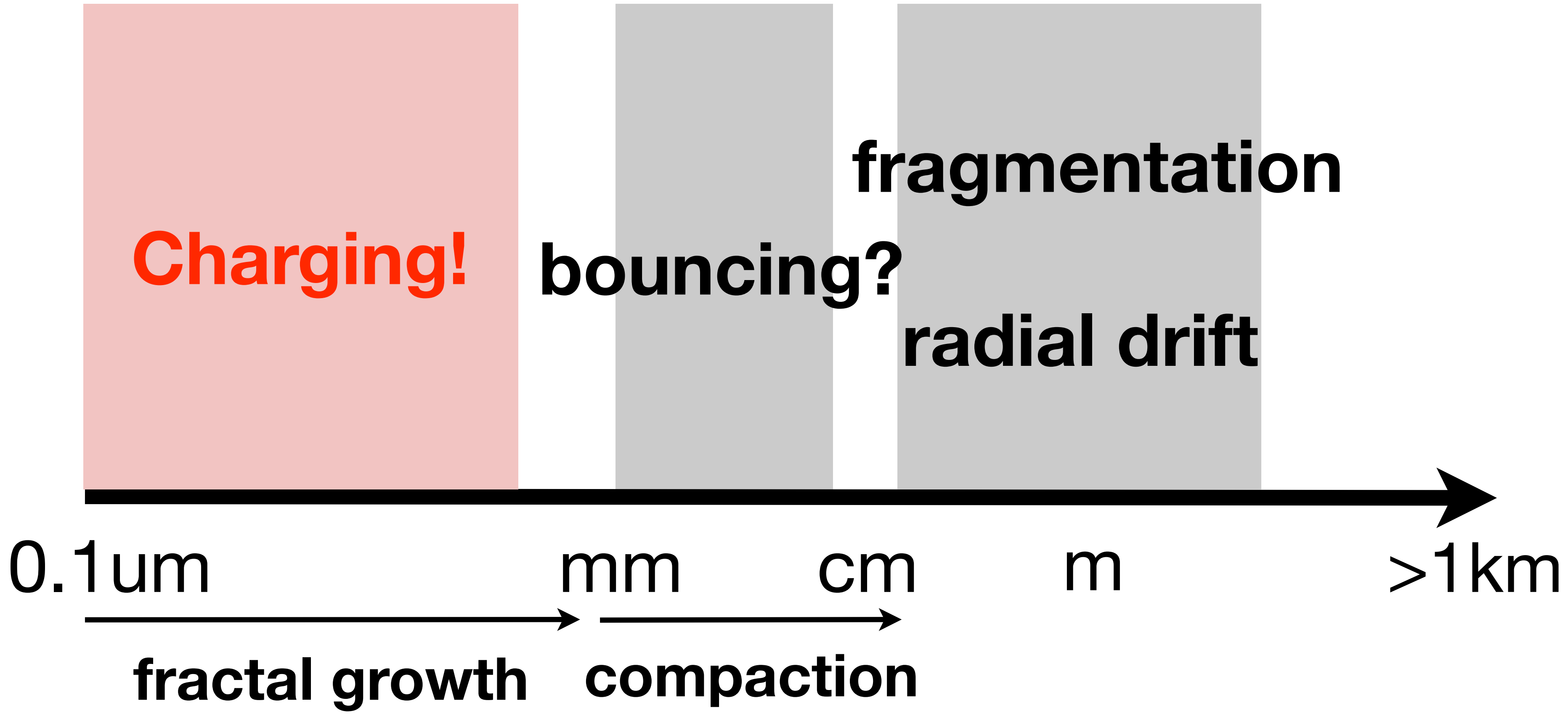
W/ charging, $\tau_{\rm grow} \sim \frac{\Sigma_g}{\Sigma_{\rm grow}} \frac{\Sigma_g}{\Sigma_d} T_{\rm K}$

$\sim 10^6$ yr @1AU

$\sim 10^5$ yr @100AU



Conclusion



Charging!

bouncing?

fragmentation

radial drift

0.1um mm cm m >1km

fractal growth

compaction

- Charging prevents dust growth before compaction occurs!
- At least, the “frozen” tiny aggregates are retained in the disk over a timescale of 10^6 years!